UNIVERSITY OF OSLO

DOCTORAL THESIS

Seven essays on policies and international cooperation to abate emissions of greenhouse gases

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A thesis submitted in fulfilment of the requirements for the degree
Dr. Philos.
at the

Department of Economics

June 2015

Series of dissertations submitted to the
Faculty of Social Sciences, University of Oslo
No. 564

ISSN 1504-3991

Cover: Hanne Baadsgaard Utigard.
Print production: John Grieg AS, Bergen.

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Contents

List of essays

Essay 1
Renegotiation-Proof Climate Agreements with Full Participation: Conditions for Pareto-Efficiency
Joint work with Geir B. Asheim
Published in *Environmental and Resource Economics*

Essay 2
International emissions trading in a noncooperative climate policy game
Joint work with Dag Einar Sommervoll
Extended version of article published in *Economics Letters* (B. Holtsmark & Sommervoll, 2012)

Essay 3
Permit Trading: Merely an Efficiency-Neutral Redistribution away from Climate-Change Victims?
Joint work with Odd Godal
Published in *Scandinavian Journal of Economics*

Essay 4
Harvesting in boreal forests and the biofuel carbon debt
Published in *Climatic Change*

Essay 5
Quantifying the global warming potential of CO_2-emissions from wood fuels
Published in *GCB Bioenergy*

Essay 6
A comparison of the global warming effects of wood fuels and fossil fuels taking albedo into account
Sligthly revised version of paper published in *GCB Bioenergy* (B. Holtsmark, 2015a)

Essay 7
Faustmann and the Climate
Joint work with Michael Hoel and Katinka Holtsmark
Published in *Journal of Forest Economics*

Preface

The thesis consists of seven essays on climate policy and international environmental agreements. All essays have been written after I returned to the Research Department at Statistics Norway in 2002. I am grateful for the opportunity given by my employer to do research on environmental and resource issues.

Environmental issues have been an interest of mine since I was a schoolboy back in the 1970s and I became aware of the book “Limits to growth”. I was also much influenced by “Thinking about the future” (a critique of the first mentioned book), which my father gave me.

Four of the essays of the thesis are joint work with some very bright and kind individuals. It has been a privilege for me to cooperate with all of you.

The first essay is a joint work with Geir B. Asheim. Working with Geir was intense and I learned a lot from this cooperation. To keep up with Geir’s progress and irregular working hours, I in periods had to work really long days and nights irrespective of weekends and holidays.

Dag Einar Sommervoll gave important contributions to the second essay, especially the proof of its main result. With his keen sense of humor in addition to his mathematical skills, it was a pleasure to work with Dag Einar.

Also Odd Godal has a keen sense of humor. The third essay, with its beautifully clear result, was the outcome of hard work and many discussions between us. Odd lives in Bergen and we therefore almost never saw each other. This was compensated for by phone talks that sometimes went off track and ended up with discussions related to other important questions of life. We became close friends during the work with this essay.

The last essay is a joint work with Michael Hoel and my daughter Katinka Holtsmark. I have known Michael since I was his research assistant in a project related to the European gas market in the 1980s. Our paths have crossed several times since then. Michael has at all occasions supported me and made me believe in my ideas and skills. Over the years we have made several articles together, both for newspapers, magazines and journals. Michael’s creativity and enthusiasm combined with his always scientific, open-minded approach have been a great inspiration.

It was also very fruitful to have my daughter involved in the work with the last essay. She solved quickly some mathematical challenges that I did disentangle and became impressively soon an important person in the author team.

Although I had a head start of 28 years, Katinka caught me up and submitted her thesis before me. Her extremely high productivity during her pregnancy impressed me and the submission of her thesis inspired me to submit my own after all these years.

With regard to the last four essays, I am grateful to Trygve Refsdal, who back in February 2010 contacted me and urged me to analyze the climatic consequences of bioenergy from forests. Shortly after, I was downright hooked trying to understand and model the fascinating dynamics of forests. At the first stage of this work, I also received important inputs from Ketil Flugsrud, Rasmus Astrup, Lise Dalsgaard, Hans Goksøyr and Olav Norem.

Communicating my research on bioenergy has meant many controversies with other researchers, policy makers, and representatives from the bioenergy business. This was not fun. Without support and encouragement from good colleagues, friends and family who believed in my ideas, I would definitely have given up this project. I will especially thank my father who passed away last year, my brother Sven Holtsmark, Hans Henrik Ramm, Trond Amundsen, Jørgen Randers, Taran Fæhn, Bente Halvorsen, Per Arild Garnåsjordet, and Iulie Aslaksen

Last, but not least, I am grateful for the life-long support from the wonderful woman in my life, Margit, who I was so fortunate to meet back in the 1970s, when we both were active in the environmental movement.

Later Margit gave me Katinka, Ole Kristian and Yngve. Their independent choices, hard work and impressive achievements have been of great inspiration to me.

Oslo, June 20, 2015.

Bjart Holtsmark

1. Introduction and summary*

The thesis consists of seven essays dealing with policies to mitigate climate change. The first three essays analyze aspects of international cooperation to abate emissions. More specifically, the first essay studies the design of a compliance mechanism when there is an international agreement on emission cuts. The next two essays analyze the effects of an international agreement with emissions trading, assuming that the national emission quotas are not results of an efficient international bargaining process, but instead are determined individually by national governments. The last four essays study how management of forests and use of wood-based bioenergy influence the accumulation of CO_2 in the atmosphere, and how forest management should be adjusted when accumulation of CO_2 in the atmosphere is considered to be socially damaging.

The thesis applies different methods. While the first three essays on international climate cooperation apply microeconomic theory and game theory, the last four essays on forest management combine basic microeconomic theory with life-cycle assessments, building on biological knowledge on the dynamics of forests and the interaction of the carbon stocks.

1.1. Background

Svante Arrhenius (1896) was the first scientist to estimate the global warming effect of an increasing concentration of CO_2 in the atmosphere. Arrhenius was aware that combustion of fossil fuels has the potential to increase the atmospheric CO_2 concentration and thus cause global warming. However, with the relatively low global emissions in the 19th century, it was not primarily global warming and climate change that was Arrhenius' concern. The foremost motivation for Arrhenius' work was to provide insights into the mechanisms behind the variations in global temperature during the Earth's geological history.

Global CO_2-emissions were relatively low also throughout the first half of the 20th century. However, following the Second World War the combination of a rapidly increasing world population and strong economic growth in many regions caused the use of fossil fuels to increase rapidly and CO_2-emissions to increase correspondingly. The emission growth has been especially high throughout the most recent decades. Roughly one third of all historical emissions of CO_2 has occurred since the turn of the millennium and emissions are likely to continue rising in the decades to come (World Energy Outlook 2014, International Energy

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* I gratefully acknowledge valuable comments to a draft from Mads Greaker, Kjetil Telle, and Åsmund Sunde Valseth.

Outlook 2014) . This has resulted in concerns that the subsequent growing concentration of CO_2 and other greenhouse gases (GHGs) in the atmosphere is causing global warming and harmful climate change (IPCC, 2014b).

Many countries have implemented policies to limit their emissions of GHGs. Moreover, for more than two decades there have been international negotiations within the Framework Convention on Climate Change (UNFCCC, 1992). This convention does not specify any quantified and legally binding emission reduction commitments. Such commitments were included in the Kyoto Protocol (UNFCCC, 1997), although the national quotas specified were too generous to mean significant emission cuts (Böhringer, 2002; Hagem & Holtsmark, 2004). As only developed countries had emission limitations, the first commitment period of the Kyoto Protocol regulated less than 30 per cent of global emissions, and the agreement on the second commitment period put limits on even fewer countries and a correspondingly smaller share of global emissions. Moreover, negotiations for an effective, comprehensive international climate agreement to follow on from the Kyoto Protocol have shown little progress. Therefore, it appears to be an important task to study how international negotiations and agreements could be more effective. This is the main motivation for the first three essays of the thesis.

While the first three essays study international cooperation on emission abatement, the last four essays study one type of abatement policy, namely the use of bioenergy as an alternative to fossil fuels. Recent reports show that there are researchers with optimistic views on the potential role of bioenergy in global energy supply and as a tool to mitigate climate change, while others are more pessimistic and emphasize that there are also many environmental concerns related to increasing use of bioenergy, see for example Haberl, Erb, et al. (2013), IPCC (2011), and IPCC (2014a).

I will at this point add that also my research on bioenergy partly has its origin in the slow progress in the international climate cooperation. From my work on international cooperation, I found it unlikely that an effective, global climate agreement will be implemented and also other reasons why it appears likely that global GHG-emissions will be high over large parts of the 21st century (B. Holtsmark, 2006, 2013b; B. Holtsmark & Alfsen, 2005; Røgeberg, Andresen, & Holtsmark, 2010). This means that the limits for the CO_2-concentration considered as dangerous most likely will be exceeded within this century. From this perspective, there is a need for measures that will give results in this century and not measures that will enhance the CO_2-concentration within this time scale. When I after some preliminary work found reasons to believe that large-scale increased use of bioenergy from forests is likely to *increase*, not reduce, the CO_2-concentration over the entire 21st century, I found this worth further investigation.

Before I introduce the essays further, I will emphasize that this thesis does not enter into the discussion of to what extent there are reasons for alarm with regard to human influence on climate change. That discussion is beyond the scope of the thesis. Rather, the starting point for the essays is that policies to reduce GHG emissions have been and will be implemented in many countries. Hence, it is important to study the effects and costs of implemented and proposed policy measures. Moreover, as there have actually been international climate negotiations for decades, and these are likely to continue, it is valuable to provide insights into the effects of proposed agreement designs. Note also that the four essays on bioenergy and forest management have relevance to international climate negotiations, as the questions of climate neutrality of biomass and land use change are important in these negotiations.

1.2. The tragedy of the commons

The starting point for the thesis is that the atmosphere is a global commons, into which we discharge our industrial CO_2 and other GHGs. The approach worked for a long time, but according to IPCC (2014b) the system is evidently straining under the load. The more GHGs in the atmosphere, the greater the adverse impacts on the Earth's climate (IPCC, 2014b). At the same time each individual or country will have weak incentives to reduce their own emissions while the potentially dangerous amounts of GHGs accumulate in the atmosphere.

Garrett Hardin picturesquely described the problem studied in his article "The Tragedy of the Commons" in *Science* in 1968. Hardin drew and expanded on a story given in an 1833 lecture by William Forster Lloyd, then professor of political economy at Oxford.[1] The story is that several cattle-owners are allowed to let as many cows as they like graze a common open pasture, and do so without encountering problems. The capacity of the land is limited, however, and as the populations grow a point will inevitably be reached when "the inherent logic of the commons remorselessly generate(s) [a] tragedy" (Hardin, 1968, p. p. 1244).

The question each cattle-owner has to ask is "What is there to be gained from adding an extra cow to my herd?" The positive component comes from the sale of the additional quantities of beef, milk and hides provided by the additional cow. The negative component is

[1] As Copeland and Taylor (2009) noted, Hardin primarily popularized and raised awareness of the problems of resource management. He did not provide a complete analysis of the problems arising from free access to a resource.

the added pressure on the land, causing the productivity of the owner's original livestock to decline. The "tragedy of the commons" follows from the failure of each individual cattle-herder to take into account the effect on the productivity of all the other farmers' livestock. Without proper cooperation between the cattle-owners, the result is likely to be overgrazing and a general loss of welfare.

As Harding puts it, "Each man is locked into a system that compels him to increase his herd without limit – in a world that is limited." The basic purpose of the thesis is to be a contribution to the accumulation of knowledge on how society can escape from such traps.

1.3. Weak incentives to reduce emissions of greenhouse gases – numerical examples

Just as the cattle owners have strong incentives to increase their herd, countries have weak incentives to reduce their emissions of GHGs. Table 1 illustrates this. The table shows estimated reduction in global warming in 2025, 2050 and 2100 resulting from individual emission cuts by the world's three greatest countries, joint cuts by the group of developed countries, and joint cuts by the whole world, respectively. The temperature reductions caused by emission cuts are calculated using an impulse response function (IRF) derived from the carbon cycle model Bern 2.5CC (Joos & Bruno, 1996; Joos et al., 1996; Joos et al., 2001). This IRF was selected in the IPCC Fourth Assessment Report (IPCC, 2007) as their preferred model and is also applied in the fifth and sixth essays of this thesis. The applied model implies a climate sensitivity of 3 °C.[2] The numerical examples of Table 1 are based on model simulations described in B. Holtsmark (2013b). In the reference scenario the global temperature is approximately 2.3 and 4.2 °C higher in 2050 and 2100, respectively, compared to pre-industrial temperatures.

It is perhaps obvious that small countries have modest incentives to reduce domestic emissions. However, Table 1 illustrates that large countries, as the USA and China, also have weak incentives to cut domestic emissions. Moreover, the table shows that even the entire group of industrialized countries acting collectively together with China, will not achieve very much unless the rest of the world joins in.

For example, the third column in Table 1 shows a case where China follows a path implying extensive emissions cuts of 15, 65 and 95 per cent compared to the business-as-

[2] According to IPCC (2007, p. p. 38) "the climate sensitivity of carbon dioxide is usually defined as the equilibrium global average surface warming following a doubling of CO_2 concentration." Moreover, "climate sensitivity [of CO_2] is likely to be in the range of 2 to 4.5°C with a best estimate of about 3°C, and is very unlikely to be less than 1.5°C." IPCC (2013) did not provide a best estimate of the climate sensitivity of CO_2.

usual (BAU) levels in 2025, 2050 and 2100, respectively. The numbers in this column isolate the temperature effect of China's emission reductions. The result would be a relatively modest slowdown in global warming; 0.01 °C, 0.07 °C, and 0.23 °C lower global temperature in 2025, 2050 and 2100 than in BAU, respectively. The corresponding numbers are similar or smaller for India and the USA, see the two subsequent columns of Table 1.

These numerical examples suggest that a single country's efforts, even over a very long period, will have a relatively small impact on global temperature change, also when the biggest countries of the world are considered. One should keep in mind that emission cuts of the size considered in Table 1 are costly, at least politically, to implement. Such emission cuts will, for example, require high taxes or other instruments that will have significant effects on end-user prices on energy. With weak climatic effects, as illustrated in Table 1, it could be difficult to have political acceptance for such policies. It follows that a joint effort by all or most countries in the world is likely to make more sense to the public and policymakers in the respective countries. This emphasizes the importance of knowledge on how international agreements should be designed, which is the topic of the first three essays of the thesis.

*Table 1. The slowdown in global warming when China, India or the USA unilaterally cuts emissions and if all developed countries or the whole world do the same.**

	Emission reductions from BAU*	Temperature change compared to no action °C				
		China	India	USA	All developed countries	Global action
2025	-15 %	-0.01 °C	-0.002 °C	-0.01 °C	-0.02 °C	-0.04 °C
2050	-65 %	-0.07 °C	-0.03 °C	-0.06 °C	-0.12 °C	-0.36 °C
2100	-95 %	-0.23 °C	-0.12 °C	-0.16 °C	-0.30 °C	-1.56 °C

*In the assumed BAU scenario China's CO_2 emissions are set to rise from 5.8 $GtCO_2$ in 2010 to 11.0 $GtCO_2$ in 2100. By assumption India's and the US BAU emissions will rise from 1.6 to 5.5 $GtCO_2$ and from 6.0 to 7.0 $GtCO_2$ over the period, respectively.

Source: B. Holtsmark (2013b)

1.4. Stable agreements and participation

It follows from the numerical examples in Table 1 that joint efforts by a significant group of countries, i.e. an international climate agreement, might be necessary to gain public support for large emission cuts on a global scale. At the same time, there are significant potential gains from freeriding on an ambitious agreement implemented by other countries. Free-riding occurs when a party receives the benefits of a public good without contributing to the costs (Nordhaus, 2015, p. p 1339). The question then is how agreements could be designed to overcome the incentives to free ride. At this point one should distinguish between *participation* and *compliance,* although these concepts cannot be analyzed in isolation to each other. The incentives to *participate* in an international environmental agreement is in the literature often analyzed by the use of non-cooperative game theory as originally conceived by d'Aspremont, Jaquemin, Gabszewicz, and Weymark (1983) in their study of cartels, see also Finus (2008) for an overview of related literature. The cartel-based concept leads to relatively pessimistic results on the prospects of the climate negotiations, which I will return to below. However, it should here be mentioned that another approach, taken by Chander and Tulkens (1995), see also for example Chander (2007), who find that the grand coalition is an equilibrium.

A coalition is defined as internally stable if each coalition member is better off as member of the coalition than as an outsider.[3] Using this concept in a model with quadratic abatement cost functions and linear climate damage functions, Barrett (1994) found that a coalition of more than three countries would be unstable, see also Hoel (1992). Before turning to a discussion of the compliance problem, an introduction to this frequently cited result is appropriate. This also serves as an introduction to the models applied in the first and the second essays. Moreover, the third essay contains a numerical example that applies a similar linear-quadratic model.

Consider a world with a set N of n identical countries. Denote the abatement in country i as q_i. Emission reduction is a public good; in other words, each country benefits from the overall emission reduction. Assume a linear relationship between global emission abatement and each country's benefits, expressed by $b\Sigma_i q_i$, where b is a positive parameter. The benefits of emission abatement are less damage from drought, warmer weather and so forth, and lower costs of adaptation to impacts, such as a rising sea level. Assume that the abatement cost function is quadratic.[4] If country i is to cut its emissions by q_i units, the cost is given by $(c/2)(q_i)^2$, where c is a positive parameter.

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[3] The literature distinguishes between *internal* and *external* stability (Carraro & Siniscalco, 1993). A coalition is *internally* stable if no signatory would be better off leaving the coalition, while a coalition is *externally* stable if no outsider would be better off joining the coalition. I will in the following focus on internal stability, and for simplicity use the term *stability* for short.

[4] This is a frequently used functional form in the literature; see for example Barrett (1994) and Barrett (2003).

In the analysis below, the results are not influenced by the values chosen for b and c. To simplify, I therefore assume that $b = c = 1$. The payoff for country i then is:

$$v_i = \Sigma_{j \in N} q_j - \tfrac{1}{2} (q_i)^2, \; i = 1,2, \ldots, n. \tag{1}$$

Maximizing v_i with respect to q_i gives the abatement level $q^1 = 1$. Hence, if each country sticks to this abatement level, there is a Nash equilibrium in the sense that no player has anything to gain by changing his own strategy. If all countries choose the abatement level $q^P = n$, the joint welfare is maximized. Note that $q^P > q^1$.

Let us now assume that k of the n countries agree to reduce their emissions by k units each. An abatement level k is chosen because it level will maximize the joint welfare of the coalition countries. The remaining (n-k) countries, the outsiders, stick to the Nash equilibrium abatement level $q^1 = 1$, as this maximizes their individual payoffs.

Let v_{sk} be the payoff to a signatory to the agreement when there are k coalition members. From equation (1), we obtain that

$$v_{sk} = k^2 + (n\text{-}k) - \tfrac{1}{2} k^2. \tag{2}$$

Next, assume that one country withdraws from the agreement. The k-1 remaining signatories will maximize their joint welfare if they adjust their agreed abatement level to k-1, while the withdrawn country will choose its dominant strategy, which is abatement level $q^1 = 1$. Let v_{nk} be the payoff to an outsider. After withdrawal from an agreement with k parties, the payoff to the new outsider will be given by

$$v_{nk\text{-}1} = (k\text{-}1)^2 + (n\text{-}(k\text{-}1)) - \tfrac{1}{2}. \tag{3}$$

From (2) and (3) we can obtain the gain from participation:

$$v_{sk} - v_{nk\text{-}1} = \tfrac{1}{2}(k\text{-}1)(3\text{-}k). \tag{4}$$

It follows that without any agreement in the first place ($k = 1$), two countries will increase their payoffs if they come together and agree to increase their abatement level to $q^2 = 2$. If a third country joins the coalition, it will neither lose nor gain. However, as the expression in (4) is negative if $k > 3$, an outsider will lose by joining the coalition if it already includes least three signatories. Moreover, if an agreement includes four parties or more, a signatory will benefit from withdrawal (Barrett, 1994).

With regard to intuition to equation (4), one key factor is that the larger is a coalition, the deeper emission cuts will maximize the coalition's joint welfare. Thus, the larger is a coalition, the greater are the avoided abatement costs to a free-rider.

A reasonable question is how far the result that follows from equation (4) can be generalized. As I have pointed out, the values of parameters b and c do not affect the result.[5] On the other hand, other functional forms might lead to different results.

Of greater importance is probably the lack of dynamics in this type of games. Battaglini and Harstad (2015), Harstad (2012), Harstad (2015) apply dynamic models and are therefore able to include many strategic aspects of the formation of climate agreements that are neglected in the static games described above. It is therefore noteworthy that they find equilibriums with much larger coalitions.

There are also other reasons to be more optimistic than the result above indicates. Some studies have found that with heterogeneous countries and side payments, stable coalitions could be larger and agree on deeper emission cuts. For example, McGinty (2007) found that a stable coalition of 20 different signatories can result in 47 per cent of the difference between the full and no-cooperative solution, compared with 5 per cent for 20 identical nations. Furthermore, 72 per cent of the global payoff difference is obtained, relative to 9 per cent for identical countries. B. Holtsmark (2013b, p. p 340) reported similar results.

1.5. From participation to compliance – introduction and summary of the first essay

The game used to analyze the participation problem in the previous section assumes that if an agreement is reached, the signatories comply with their commitments to cut emissions. The question then arises how the agreement should be designed to actually provide incentives to comply. This is the topic of the first essay. Note here that despite the participation and incentive problems described above, the first essay assumes that the global community, or at least a group of countries, actually *is* able to come together and agree on emission cuts.

Compliance mechanisms cannot be discussed within a one shot game, where punishment could never be carried out. The first essay therefore introduces a repeated game in the sense that the countries interact in periods 0, 1, 2, ….. In each period the countries' payoffs are described by equation (1). Moreover, if there is an agreement among k countries to maximize their joint welfare, the coalition members' undiscounted payoffs in each period are described by equation (2).

[5] If we do not assign numerical values to b and c, equation (7) will read as follows: $v_{sk} = v_{nk-1} + ½b^2(k-1)(3-k)/c$. Hence, the gain resulting from participation is equal to $½b^2(k-1)(3-k)/c$. This expression is non-negative if $1 \leq k \leq 3$. A coalition of more than three countries will therefore be unstable irrespective of the size of b and c, provided they are positive, see Barrett (2005) and Hoel (1992).

However, within the model introduced in the previous section, and without any additional incentives, compliance will not pay off and the signatories are best off if they deviate and choose the Nash-equilibrium's abatement level $q^1 = 1$. Barrett (1999) therefore analyzed whether compliance would pay off if all complying signatories punish a deviating country by reducing their abatement level to $q^1 = 1$ in the period after the deviation. Assuming that all the n countries have joined the coalition, a country that deviates and abates $q^1 = 1$ in period 0, would then collect the following discounted payoffs in period 0 and 1:

$$v(0,1)_{defection} = [(n-1)n + 1 - ½] + \delta\,[n + (n-1) - ½\,n^2], \tag{5}$$

where δ is the discount factor. The discount factor is defined as $\delta \coloneqq 1/(1+r)$, where r is the discount rate. With compliance, payoff would be:

$$v(0,1)_{compliance} = (1 + \delta)\,[n^2 - ½\,n^2]. \tag{6}$$

It follows that $v(0,1)_{defection} < v(0,1)_{compliance}$ if, and only if, $r < 1$. In other words, the punishment rule will make compliance pay off.

However, as Barrett (1999) found, this does not help very much if there are many signatories. They will all gain by renegotiating back to cooperation without imposing the punishment, thereby undermining the credibility of the punishment. Recall that if the punishment is carried out, the punishing countries' undiscounted payoffs in period 1 will be

$$n + (n-1) - ½. \tag{7}$$

However, instead of carrying out the punishment, they could ask for renegotiation and propose that all signatories immediately return to the abatement level $q^n = n$. That would give the period 1 payoff:

$$n^2 - n^2/2. \tag{8}$$

It follows that renegotiation gives a strictly higher payoff if $n \geq 4$. Taking into account that also the deviating country will be better off with renegotiation, it follows that with at least four signatories they will all be strictly better off with renegotiation. Thus, the punishment threat is not credible. And Barrett (1999) and (Barrett, 2002) concluded that there is a trade-off between "narrow but deep" and "broad but shallow" agreements: credible punishment rules could only be designed if either only a few countries participate, or many countries participate with small emission cuts.

Two questions then arise. First, could the described credibility problem be overcome with a different punishment rule? Second, could a different punishment rule overcome the trade-off between depth and broadness found by Barrett?

The first of these two questions was analyzed by Froyn and Hovi (2008). Within the binary abatement choice model of Barrett (1999), and building on the approach taken by Asheim, Froyn, Hovi, and Menz (2006), they found that the credibility problem could be overcome if *only a subset of the signatories within a global treaty punishes a deviating country in the next period*. Froyn and Hovi (2008) found that a credible compliance rule could be constructed along these lines even in a global agreement. [6]

However, the binary abatement choice model applied by Asheim et al. (2006) and Froyn and Hovi (2008) makes the simplifying assumption that countries either abate one emissions unit or do not cut emissions at all. This type of model does not take into account that governments in reality could choose abatement levels along an almost continuous scale and, furthermore, that marginal abatement costs usually are increasing along this scale. This means that the abatement level (the depth of cooperation) that maximizes the joint welfare of a coalition of countries is increasing in the number of participating countries.[7] For example, considering the linear-quadratic model introduced in the previous section, the abatement level that maximizes the joint welfare of a coalition is proportional to the number of signatories. This important benefit from international environmental agreements is, for example, lost when the binary model is applied.

Due to the limitations of the binary choice model, it is important to check whether the results of Asheim et al. (2006) and Froyn and Hovi (2008) carry over to the models with continuous and strictly convex abatement cost functions. Moreover, the binary choice model, with a fixed depth of cooperation, cannot be used to analyze the second question raised above; whether a different punishment rule could overcome the problem that a broad treaty has to be shallow. Essay 1, which is a joint work with Geir B. Asheim, studies these questions. Moreover, the use of the continuous choice model allows for more detailed analysis of how credible punishment rules could be designed. The essay has been published in *Environmental and Resource Economics* (Asheim & Holtsmark, 2009).

The first essay finds, as its main result, that an efficient, broad and deep treaty can always be implemented as a weakly renegotiation-proof equilibrium, as defined by Farrell and

[6] Other types of enforcement mechanisms are analysed in the literature, for example trade sanctions, see Barrett (2008), Nordhaus (2015) or Hovi, Greaker, Hagem, and Holtsmark (2012), among others.
[7] If the countries have differently shaped abatement cost functions and different benefit functions, the depth of cooperation also depends on which countries participate.

Maskin (1989), if the discount rate is sufficiently low. As in Froyn and Hovi (2008), the solution is a compliance rule saying that only a *subgroup* of the complying signatories should punish the deviator, while the remaining signatories should stick to the agreed abatement level. The point here is that if the discount rate is sufficiently low, the rule then could be designed such that the punishing countries never will be willing to renegotiate, because they benefit from the abatement carried out by the complying countries that are supposed to stick to the Pareto-efficient abatement level.

For example, in the four-country-case, after a deviation in period t only two of the complying countries should reduce their abatement level in period $t+1$, while the third of the complying countries should stick to the Pareto-efficient abatement level. If the discount rate is sufficiently low, compliance will then pay off while the punishing countries are not willing to renegotiate.

The first essay includes an additional result showing how the depth of cooperation must be reduced for high discount rates. To stick to the four-country-example; the result means that if the discount rate is above approximately 0.44, then the Pareto-efficient abatement level could no longer be achieved as a weakly renegotiation-proof equilibrium. Figure 1 in the first essay shows how the abatement level has to be reduced as the assumed discount rate is increased. Note here that discount rates above 0.44 cannot be ruled out, as the period length considered is not necessarily one year, but more likely longer. Recall that the relevant length of the time period is determined by different factors, not least the time lag between a deviation and implementation of punishments. Punishments cannot be carried out before emission accounts are reported and properly reviewed, and so forth. Hence, the relevant time period is likely to be a number of years.

After the publication of the first essay in *Environmental and Resource Economics* in 2009, some papers have followed up the analysis. Heitzig, Lessmann, and Zou (2011) constructed a model with some similar features and propose other compliance mechanisms that will make compliance pay off and avoid renegotiation. Kratzsch, Sieg, and Stegemann (2012) point to the fact that Asheim et al. (2006), Asheim and Holtsmark (2009), and Froyn and Hovi (2008) consider *emissions* as the damaging factor. Kratzsch et al. (2012) improve the binary abatement choice model by taking into account that the accumulated *stock* of pollutants in the atmosphere is the relevant damaging factor, see also Hoel and Karp (2002) and Hoel and Karp (2001). Kratzsch et al. (2012) therefore analyzed renegotiation proof equilibriums and found that the results of Froyn and Hovi (2008) carry over to a binary choice model with a stock pollutant. It remains to show that their results considering a stock pollutant carry over to a continuous abatement choice model.

1.6. Permit trading without efficient bargaining of quotas – introduction to the second and third essays

Section 1.4 and the first essay studied situations where cooperating countries bargain efficiently in the sense that they agree on a set of national emission quotas that maximizes the signatories' joint welfare. This is a common approach in the literature on international environmental agreement.

The approach of the second and third essays is different and less optimistic and are contributions to a smaller literature that has its origin in Helm (2003). This literature studies cooperation when national quotas result solely from strategic national interests, not efficient bargaining. This approach has its motivation both in the pessimistic results in some of the contributions to the mentioned literature on international environmental agreements and in the development of international climate cooperation over the last decades. Indeed, there are as mentioned some recent contributions that give reasons to be more optimistic (Battaglini & Harstad, 2015; Harstad, 2012, 2015). However, both the simple participation game introduced in section 1.4 and the numerical examples presented in section 1.3 emphasize the difficulties related to international climate cooperation. Moreover, the international climate talks have resulted in little agreement other than the Kyoto Protocol. It is, as mentioned, usually concluded that the aggregate target of the countries that ratified the treaty and made a quantified commitment, is not substantially different from the signatories' aggregate business as usual emissions; see, e.g., Springer (2003) for a survey. Hence, although well furnished with good intentions, international climate talks this far have resulted in few outcomes that resemble efficient bargaining and collective behavior.

The relevance of the chosen approach taken in the second and third essays could be illustrated by the Copenhagen Accord, the agreement reached at the 15th Conference of the parties to the Climate Convention in Copenhagen in 2009 (UNFCCC, 2009). The Accord envisages emission cuts. However, the sizes of the national quotas were not specified after negotiations at the meeting. Instead, the Accord concluded that the signatories should individually quantify their national quotas *after* the meeting and submit these emission targets to the secretariat of the Climate Convention without any further bargaining (UNFCCC, 2009, p. § 4).

Despite the described lack of efficient bargaining in determination of national emission quotas, emissions trading has retained its key position in the climate talks. For example, the Copenhagen Accord, §4, states that commitments could be carried out jointly, which means that the agreement allows emissions trading. The reason is obviously the efficiency arguments for international emissions trading. When the initial allocation of permits is considered as already given and fixed, these arguments are well established. Quite simply, voluntary exchange cannot harm any trading party but is likely to give efficiency gains. Moreover, this policy instrument has further been identified as a promising tool when the initial allocation is not already given, but rather is part of the problem. The reason is that it can serve as a vehicle to facilitate side payments in international negotiations. Such payments have the potential to broaden international participation and deepen the emissions cuts.

The question, however, is whether these promising aspects of emissions trading apply in a world with less efficient bargaining. The purpose of the second and third essays of this thesis is to examine some possible consequences of emissions trading in a fairly fragmented world where governments struggle to maximize their collective objectives. The underlying assumption is that decisions are better reflected by governments optimizing on individual concerns along the lines considered in the studies by Helm (2003) and Carbone, Helm, and Rutherford (2009). In this type of setting, governments that decide to take on quantified international commitments, select their quotas individually without any bargaining with other governments. Still, the governments recognize each other's emission permits as transferable documents.

What could such a setting deliver in terms of overall efficiency and emission cuts? To address this question, the second and third essays, for purpose of comparison, also consider the classical case (labeled *policy A*), where governments decide individually and voluntarily on their national emission levels while emissions trading does not take place. If we abstract from problems of carbon leakage, the marginal domestic abatement cost then becomes equal to the aggregate national marginal benefits of emission abatement.

There are two sources of inefficiency associated with policy A. First, due to the weak incentives for individual emissions reductions discussed above, global emissions are too large. Second, when abatement levels are such that marginal domestic abatement costs become equal to the aggregate national marginal benefits of emission abatement, abatement efforts are inefficiently allocated because damages from climate change caused by GHG emissions will vary between countries.[8] To eradicate the latter cause of inefficiency, one could combine an international emissions trading system (called *policy B*) with policy A. Indeed, if countries' original endowments of emission allowances (targets, for short) were fixed at the emissions levels of policy A, trading (policy B) would yield efficiency gains, to no countries' disadvantage.

The key point of the second and third essays is that trade (policy B) creates incentives that are absent under policy A alone. The establishment of an international permit market creates prospects of revenues for national economies by export of emission allowances. Therefore, the second and third essays consider cases where the emission targets are not fixed at the levels of policy A, but instead are influenced by governments' anticipation of emissions trading with potential revenues.

The second essay is limited to an analysis of the combination of policies A and B. The third essay goes a step further and takes into account that fossil-fuel taxes and subsidies (*policy C*) are in widespread use (IEA, 2014; OECD, 2013). The effective price of carbon is determined not only by the permit price, but also by such taxes and subsidies. In similar lines as discussed in Hoel (1993, p. p 224), the third essay addresses that an international agreement could *change* the involved governments' design of their fossil fuels tax policy, see also Ederington (2001) for a similar discussion related to trade agreements. The contribution of the third essay is to combine domestic emission taxes and subsidies, policy C, with policies A and B. This is then compared to a situation without emissions trading, i.e. a combination of policies A and C only.

1.7. Effects of emissions trading – summary of the second essay

The second essay is a joint work with Dag Einar Sommervoll and is an extended version of an article published in *Economics Letters* (B. Holtsmark & Sommervoll, 2012).[9]

The model introduced by Helm (2003) is the starting point for the second essay. He studied a combination of policy A and B.

In contrast to the models applied in section 1.4 and in the first essay, the second essay considers at set of heterogeneous countries in the sense that both abatement cost functions and benefits from abatement vary between countries. Define countries that experience high and low damages from climate change as H-countries and L-countries, respectively. H-countries

[8] I here abstract from another source of efficiency of this case discussed in (Hoel, 2005); that countries choose carbon taxes that are differentiated across sectors. The purpose is to reduce leakage, i.e. influence emissions in other countries.

[9] The proof of the main result in B. Holtsmark and Sommervoll (2012) is compact. This is made more accessible in the second essay. In other respects, the second essay is identical to B. Holtsmark and Sommervoll (2012).

will experience high benefits from abatement, i.e. have a large b_i, while L-countries will experience low benefits from abatement, have a small b_j, where i and j are country indexes. With policy A alone, type H countries will impose ambitious emission cuts in the sense that marginal abatement costs become large. Correspondingly, L-countries will impose less ambitious targets.

With emissions trading (policy B), marginal abatement costs become equalized between countries and in the case with linear benefits from abatement, the permit price will be equal to the average of the countries' marginal benefits (B. Holtsmark & Sommervoll, 2009, p. p. 11) . This means that H-countries will carry out less abatement with trade, while L-countries will abate more. This redistribution of abatement efforts represents an efficiency gain.

However, whether trade leads to increased efficiency or not depends on the countries' adjustments of their targets when trade is introduced. Type L countries choose less ambitious targets when trade is introduced. Conversely, type H countries choose more ambitious targets (Helm, 2003). The total effect on global emissions in the model of Helm (2003) becomes ambiguous. This also applies to efficiency.

With policy A alone, global emissions are inefficiently high. Hence, if trade (policy B) leads to less abatement overall and even more inefficiently high emissions, this draws in the direction of reduced efficiency. This efficiency loss might outweigh the efficiency gains from trade. Because it is not clear whether trade leads to more or less abatement globally, it is unclear whether trade gives an efficiency gain.

The second essay extends the climate policy game of Helm (2003). In the second essay each country comprises a government and a set of identical firms. The number of firms varies between countries. Emissions stem from the firms, and they have all the same quadratic abatement cost function. It follows that each country's aggregate abatement cost function is quadratic as well.

As the first essay, the second essay assumes that the countries experience linear benefits from global emission abatement. However, now the marginal benefits from global emission abatement vary and are proportional to the number of firms in the country. This assumption reflects that the size of the benefits from abatement (avoided damages from GHG emissions) is likely to be related to the size of the economies.

The firms and the governments participate in a two-stage game. In stage 1 each government chooses an emission target, its pre-trade endowments of emission allowances. The allowances are transferred to the firms. In the second stage, all firms have access to an international permit marked while being committed to keep their emissions equal to or below their respective after-trade stock of emission permits. While the firms are price-takers, the governments take into consideration that the chosen sizes of the emission targets influence the global permit price.

In equilibrium the global permit price becomes equal to the average marginal benefits from abatement. It follows that large economies will carry out less abatement as trade is introduced, and become permit importers. Small economies will increase their abatement and become permit exporters (see also Proposition 1 in Helm, 2003).

As small countries by definition have fewer firms than larger countries, smaller countries have a steeper aggregate marginal abatement cost function than larger countries. Consequently, a large economy must typically make a greater downward adjustment of its abatement level than a typical small economy adjusts its abatement upwards. This is the basic mechanism leading to the second essay's first main result, which is that less abatement will be carried out with trade.

In addition, the first essay finds that also efficiency is reduced with trade. On the one hand, trade gives an efficiency gain due to efficient cross-border allocation of abatement. On the other hand, increased emissions from an inefficiently high level represents an efficiency loss. The essay finds that the latter effect dominates.

Section 1.9 provides a discussion related to this result.

1.8. Emissions trading combined with taxes and subsidies – summary of the third essay

The third essay is a joint work with Odd Godal, and was published in *Scandinavian Journal of Economics* (Godal & Holtsmark, 2011).

As in the second essay, the point of departure of the third essay is the classical case (policy A) where governments decide voluntarily on their emission levels without subsequent trade. Also the third essay combines policy A with an international emissions trading system (policy B). The contribution of the third essay is to introduce domestic emission taxes and subsidies and combine this (policy C) with policy A and B.

The motivation for inclusion of taxes and subsidies is their widespread use. For example, in India fossil fuel consumption subsidies in 2010 amounted to more than 1 per cent of GDP, while in Russia fossil fuel subsidies were close to 3 per cent of GDP in the same year (IEA 2011, p. 516). Subsidies are also significant in China. It has been estimated that if fossil fuel subsidies where completely phased out by 2020, global energy demand would be cut by nearly 5 per cent and CO_2-emissions by 5.8 per cent (IEA, 2011, p. p. 507). Moreover, fossil fuel taxes are also in widespread use, especially in developed countries (OECD, 2013, p. p. 12). It might be unrealistic to assume that these taxes and subsidies are fixed and independent of the countries' commitments in an international climate agreement. Therefore, the third essay analyzes how an agreement will influence the governments' incentives for setting of their subsidies and taxes on fossil fuels.

The third essay applies a less restrictive model than the second essay, as it does not adopt the model with a set of identical firms. Neither is there a restriction that the damage functions are linear. Rather, the more general formulations of the national abatement cost and damage functions of Helm (2003) are adopted. The contribution in relation to Helm (2003) is to introduce taxes and subsidies, and this turns out to have substantial effects on the solution of the game.

The main result is that when determination of the sizes of taxes and subsidies becomes part of the game, i.e. that policy A and B are combined with policy C, then the resulting profile of emissions is identical to that of policy A alone. This means that the possibility to adjust taxes and subsidies will totally undo any potential efficiency gains and emission cuts from international emissions trading, even though the permit market flourishes.

There are, however, distributional consequences of combining policy C with A and B. Countries with low domestic marginal damage costs of emissions will have lower emissions than targets; they become permit exporters. Conversely, countries with a high domestic marginal damage cost become permit importers. Because the allocation of abatement between countries is exactly as with policy A alone, this means that the introduction of trade inflicts an additional cost on countries with high damage costs from emissions, while countries with smaller costs from emissions will collect a gain from trade.

1.9. Interpretation of results of the second and third essays and closely related research

Both the second and the third essay have clear results although they do not point in the same direction. While the second essay finds detrimental effects of emissions trading, the third essay finds that emissions trading neither causes efficiency gains nor losses, but leads to the allocation of emission abatement that would take place without any trade. Although these conclusions differ, they both question whether emissions trading will always provide the efficiency gains usually expected.

It is here important to emphasize that there are other contributions that point in others directions. Not least important in that respect is the contribution by Carbone et al. (2009). They applied a computable general equilibrium model of the world economy and found that a system of internationally tradable emission permits could enhance global abatement significantly. This is in contrast to the results of both the second and third essays. How could this be explained? First, note that B. Holtsmark and Sommervoll (2009, p. p.12) found that in the type of game analyzed in Carbone et al. (2009), emissions trading leads to increased emissions if there is a negative covariance between the countries' marginal benefits from abatement and the steepness of their marginal abatement cost curves. Within the setting of the second essay, the marginal benefit of abatement is proportional to the countries' number of firms, while the steepness of the countries' marginal abatement costs curves is decreasing with the number of firms. Hence, within the model of the second essay, it follows that emissions trading will give increased emissions.

In contrast, Carbone et al. (2009) did not include any such restrictions on the relationship between the sizes of the countries and the benefits from emissions reductions. Instead, they argue that Japan and the USA, and especially Europe, will experience high benefits from abatement, while the former Soviet Union and China will experience much smaller benefits from abatement. With these assumptions together with equilibrium effects, they find promising benefits from emissions trading also in the non-cooperative setting. This emphasizes that too strong conclusions should not be drawn from the results of essays 2 and 3, although they point to some important mechanisms.

Since the second and third essays were published in 2012 and 2011, some other closely related contributions have been published.

Greaker and Hagem (2014) apply the non-cooperative approach to emissions trading introduced by Helm (2003). In addition they include in the model the effects of investments in research and development in emission abatement technologies. Their main result is that permit trading changes the strategic effects of technology investments and that emissions trading could make it desirable for industrialized countries to overinvest in technology both at home and in developing countries.

A more closely related paper is the recent contribution by Helm and Pichler (2015) who also apply the non-cooperative choices of permit endowments of Helm (2003). However, their attention is mainly on how subsidies for technology transfers influence the results, not on the effects of emissions trading. They find that subsidizing technology transfers leads to the adoption of better abatement technologies, thereby reducing international permit prices, and they find that the subsidies therefore tend to reduce countries' non-cooperative choices of endowments and thus reduce overall emissions. Moreover, they find that trading gives governments incentives to subsidize technology transfers and that trading through this mechanism gives lower overall emissions also in a non-cooperative environment. In other words, subsidies leads to improved technologies, which make emission abatement cheaper.

K. Holtsmark and Midttømme (2015) provide another recent contribution closely related to the second and third essays. They consider a game where the countries issue emission allowances non-cooperatively. They change the model by construction of a dynamic game. Moreover, they include endogenously determined investments in a clean technology. In this setting they find that there are gains from trade even when countries are identical. The mechanism is that the emissions trading option turns permits into an intertemporal strategic component. They find that if one country issues fewer permits today, other countries will respond by issuing fewer permits in the future. The reason is that fewer permits today increases current investments in green technology in all involved countries and countries will respond by issuing fewer emission allowances in the future. Hence, they find that emissions trading in the non-cooperative environment, which also is the starting point for the second and third essays of this thesis, will give reduced emissions and higher efficiency, in contrast to the results of the second essay.

The contrasting results in the research contributions described above show that there is uncertainty with respect to the effects of emissions trading in a world with limited international cooperation. With the central position of emissions trading in international climate cooperation, further research on this issue would be valuable.

1.10. Climate impacts of bioenergy from boreal forests

The vast boreal forest belt plays a crucial role in the Earth's carbon cycle. It covers large parts of Alaska, Canada, Scandinavia and Russia and stores approximately twice as much carbon as the tropical forest region and approximately as much carbon as the entire atmosphere (Kasischke, 2000). The last four essays of the thesis deal with the management of these forests from a global climate perspective and the question of whether there are climate benefits from increased use of wood-based bioenergy from these forests.

Although the starting point for my research on this issue has been the Norwegian forest and Norwegian forest policy, the findings of all four essays have a broader application with relevance to the entire boreal forest belt, which stretches over the northern hemisphere in a large circumpolar band covering large areas of Alaska, Canada, Scandinavia, and Russia.

The boreal region's climate is cold with a long winter season. The trees grow correspondingly slowly. Coniferous trees are the dominant plant form.

The boreal forests are important from other perspectives than climate, not least for recreation and with respect to biodiversity. The boreal forests are the home of some of the last intact terrestrial and aquatic ecosystems and large and diverse populations of mammals and birds.

At the same time many boreal forest areas have considerable potential for increased supply of bioenergy through boosted harvesting. For example, in Norway the current harvesting level is approximately at 30 – 40 per cent of a sustainable harvesting level (NEA 2010).[10] Therefore, the Norwegian government, as part of the national climate policy, seeks to increase the harvesting level and have implemented different subsidies and other policies to achieve this target (NMAF, 2008). Also in Sweden there is a considerable potential for increased supply of wood-based bioenergy even though the Swedish forests already, due to significant subsidies, supply approximately 100 TWh bioenergy annually (Kullander, Frank, Hedberg, Lundin, & Rachlew, 2015).

The basic question dealt with in the last four essays is whether increasing the harvesting level in the boreal forests for energy purposes will provide climate benefits or whether it could amplify climate change. The approach is interdisciplinary, taking advantage of knowledge and methods from biology, life cycle analysis and economics.

An important starting point for the analysis is that combustion of wood emits approximately as much CO_2 per unit of energy output as coal, and more if the moisture content of the wood is high, see Searchinger et al. (2009) and Hohle (2001). At the same time CO_2-emissions from combustion of biomass have traditionally been considered to be "carbon neutral", i.e. not part of the climate problem. Consequently, emissions from combustion of bioenergy should not be reported to the Kyoto Protocol and is not at the expense of the national quota.[11] For the same reason, to my knowledge, no country with carbon taxes imposes the tax on CO_2-emissions from bioenergy. Moreover, firms included in emissions trading markets are not committed to acquiring and surrendering allowances for emissions

[10] A *sustainable harvesting level* is defined as a harvesting level that could be sustained in the long term while the volume of standing wood converts to a stable level.

[11] The Kyoto Protocol, the only international climate agreement with quantified emissions reduction commitment, does not give Norway any credits for more than 1.5 MtCO2/year that is captured by forest (Höhne, Wartmann, Herold, & Freibauer, 2007). Because the annual carbon capture even in the high harvesting scenario is higher than 15 $MtCO_2$/year in any case, and emissions from combustion of bioenergy should not be reported, the Kyoto Protocol gives Norway strong incentives to increase the harvesting irrespective of its net effect on emissions.

from the combustion of bioenergy. This is also the case in the European market for emissions permits, which includes Norway.

With sustainable forest management, the harvest of one crop is replaced by the growth of a new crop. This growth reabsorbs the amount of carbon that was released by burning the first crop. It is therefore argued that combustion of biomass should not be considered as a source for global warming or climate change, i.e. 'carbon-neutral' or 'climate neutral'.

This is, to some extent, a reasonable argument in the case of crop-based biofuels when new crops within one or a few years replace those that are harvested, at least if one ignores the emissions that are generated by converting native habitats to cropland, an issue that has been analyzed in several studies, see for example Fargione, Hill, Tilman, Polasky, and Hawthorne (2008), Gibbs et al. (2010), Lapola et al. (2010), and Melillo et al. (2009). There is, however, a basic difference between bioenergy based on such rapidly growing crops and bioenergy based on wood from boreal forests. The regrowth of a typical boreal spruce or pine tree takes 70 – 120 years, and when considered mature and ready for harvest, the trees are usually still growing and still serve as carbon sinks (Storaunet & Rolstad, 2002).

Despite these well known facts, it has been common to consider wood as a carbon-neutral energy source also in scientific literature dealing with possible climate benefits from bioenergy, see for example Bright and Strømman (2009), Petersen and Solberg (2005), Raymer (2006), Sjølie, Trømborg, Solberg, and Bolkesjø (2010), and Zhang et al. (2010). These studies include thorough summing of all emissions associated with logging and processing of wood for fuel production. And they make careful track of emission reductions achieved when the considered amounts of bioenergy are assumed to replace fossil fuels. When they come to the emissions of CO_2 from the combustion of wood, however, these are simply not accounted for, due to the view that those emissions are carbon neutral. I will in the following argue that conclusions with regard to the effect of bioenergy on the net accumulation of CO_2 in the atmosphere become misleading with that approach.

It should here be noted that Tahvonen (1995) was an early contribution that did not accept the carbon neutrality assumption, but rather argued that also CO_2 emissions from combustion of bioenergy should be part of CO_2-tax regimes. More recently, a large literature has emerged showing the inadequacy of the carbon neutrality assumption related to wood-based bioenergy, see for example Chum et al. (2011), Friedland and Gillingham (2010), Haberl (2013), Haberl et al. (2012), Haberl, Schulze, et al. (2013), B. Holtsmark (2012), Hudiburg, Law, Wirth, and Luyssaert (2011), Schulze, Körner, Law, Haberl, and Luyssaert (2012), Searchinger et al. (2009), McDermott, Howarth, and Lutz (2015).

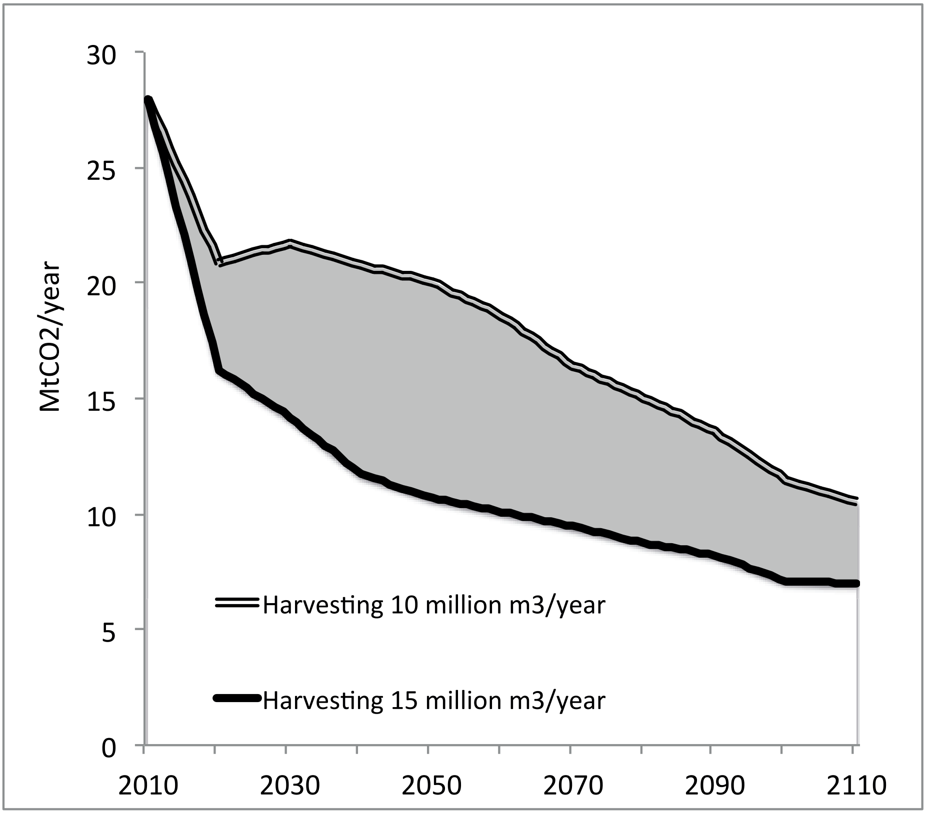

Figure 1. Annual net carbon capture in the Norwegian forest in two harvesting scenarios according to model simulations carried out at the Norwegian Forest and Landscape Institute (the NFLI-model).

Source: NEA (2010)

To illustrate the inadequacy of the carbon neutrality assumption related to bioenergy from forests, it is useful to draw attention to a report from the Norwegian Environment Agency (NEA, 2010). This report considered two harvest scenarios for the Norwegian forest for the period 2010 - 2110; one reference scenario with an annual harvesting at the current level of approximately 10 mill m^3 and a scenario in which the harvesting level is increased to 15 million m^3, which is the harvesting level defined as a goal by the Norwegian Government (NMAF, 2008). The scenarios were constructed by simulations with a model of the Norwegian forest constructed at the Norwegian forest and landscape institute (in the following labeled the NFLI-model). Figure 17.2 in NEA (2010), which is reproduced as Figure 1 below, shows that in both scenarios the forest's carbon stock is growing during the entire simulation period.[12] With regard to the question of carbon neutrality, it is noteworthy that the Norwegian forest's net annual uptake is likely to be 5 – 9 $MtCO_2$ higher in the low harvesting scenario compared to the high harvesting scenario (Figure 1).

From the figures reported in NEA (2010), it follows that over the considered simulation period of 100 years, the reduction in the forest's net uptake of CO_2, due to increased harvesting, would accumulate to approximately 650 million tonnes (the grey area of Figure 1). NEA (2011, pp. Figure 3-5) reported similar results and did also show that the result would be similar also if extensive silvicultural measures were taken.

NEA (2010) also reports the potential amount of fossil fuels that could be replaced by certain amounts for wood-based energy. According to NEA (2010, p 186), one m^3 wood could provide energy to replace fossil fuels used for heating that would have caused 0.7 – 1.0 tonnes of fossil CO_2 emissions. If instead one m^3 wood is used as raw material for production of second generation liquid biofuel and replaces petrol, it could eliminate 0.2 – 0.3 tonnes of fossil CO_2 emissions, according to NEA (2010).[13]

A simple arithmetic exercise then provides an important result: The increased harvesting level would over the considered 100 years period give 500 million m^3 of wood that could be used for energy purposes. According to the figures from NEA (2010) listed above, this amount of wood could over the entire simulation period replace an amount of fossil fuels that would have caused emissions of 100 – 500 $MtCO_2$. Relating these figures to the estimated drop in the forest's carbon stock of 650 $MtCO_2$, means that increasing the annual harvesting to the proposed level, will lead to *increased* accumulated net emissions over the 100 years simulation period of 150 – 550 $MtCO_2$ even when it is taken into account that increased supply of bioenergy replaces fossil fuel consumption.

Although NEA (2010) and NEA (2011) provided the foundation for this numerical example, which indicates that increasing use of wood-based bioenergy will mean more CO_2 in the atmosphere over the entire 21st century, those reports did not include similar numerical exercises and seem instead to take for granted that bioenergy from increasing the harvesting level is advantageous from a climate perspective.[14] Indeed, as I will demonstrate below, bioenergy also from boreal forests could provide climate benefits in the very long term.

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[12] The two scenarios reported in NEA (2010) were based on simulations with the numerical model developed at the Norwegian Forest and Landscape Institute (NFLI). NEA (2010) also considered a third scenario, but that scenario was not based on model simulations and will therefore not be analysed here.
[13] The figures in NEA (2010) had an increase of 3 millions m^3 wood as the starting point. The numbers presented here are scaled down to correspond to a single m^3 instead.
[14] For example, the project leader for Klimakur stated that "the total climatic impact [of increased extraction of wood] will be positive when one includes the effects in the long term" (Økstad, 2010).

However, the reports did not give any information on how far into the future there will be climate benefits from the Norwegian government's bioenergy policy. This and other unsolved questions were the starting points for my research, which led to the last four essays of this thesis. The research questions considered in these essays could be summarized as follows:

1. Will a different dynamic model of the Norwegian forest confirm that a higher harvesting level is going to have such a significant negative effect on the forest's carbon stock that was found by the NFLI model studies?
2. The NFLI model has a time horizon limited to 100 years. It is therefore an open question what are the very long term effects on the forest's carbon stock of increasing the harvesting level. To make a model with a wider time horizon was therefore a second task.
3. When wood fuels should no longer be considered carbon neutral, the question comes up how to quantify the climate impact of such fuels. The fifth and sixth essays apply the concept *global warming potentials* (GWP) to provide answers to such questions.
4. Fargione et al. (2008) introduced the concept "biofuel carbon debt", which is applied in the fourth and sixth essays. However, Fargione et al. (2008) did not study wood-based biofuels. It was therefore an open question whether the concept has relevance for wood-based biofuels. And if so, what is the length of the payback time?
5. After clear-cutting a stand, the snow surface during the winter season will to a large extent reflect sunlight (increased albedo). This has a cooling effect. How does this influence the net warming effect of harvesting?
6. The German forester Martin Faustmann published in 1849 a study with a rule for optimal time of harvesting (Faustmann, 1849). The last essay discusses how Faustmann's rule should be adjusted when there is a social cost of CO_2 emissions.

1.11. Introduction to the fourth essay

In the following, I will introduce the fourth essay of this thesis ("Harvesting in boreal forests and the biofuel carbon debt", published in *Climatic Change*). As some methods applied in the essay were applied in the last three essays of the thesis as well, the introduction to the fourth essay will be somewhat more comprehensive than the introduction and summary of the last three essays.

The fourth essay is based on simulations with a model of the Norwegian forest. The purpose for construction of this model, which will be called the H-model, was two-fold. First, the model simulation results presented in NEA (2010, 2011), which were based on the NFLI-model, had a 90 - 100 years time horizon and were too short to show the long term climate benefits that are assumed to be the final result (Økstad, 2010). Hence, an important task appeared to be to construct tools that could calculate the very long-term effects of wood-based bioenergy. Moreover, other scientific contributions to the discussion of climate effects of bioenergy usually have had time horizons of several centuries, see for example Fargione et al. (2008) where the time horizon is more than 800 years. A model with a wider time horizon would therefore be useful. Second, construction of a new model that is not based on the methods applied in construction of NFLI-model, would be a useful test on the reliability of the simulation results presented in NEA (2010, 2011).

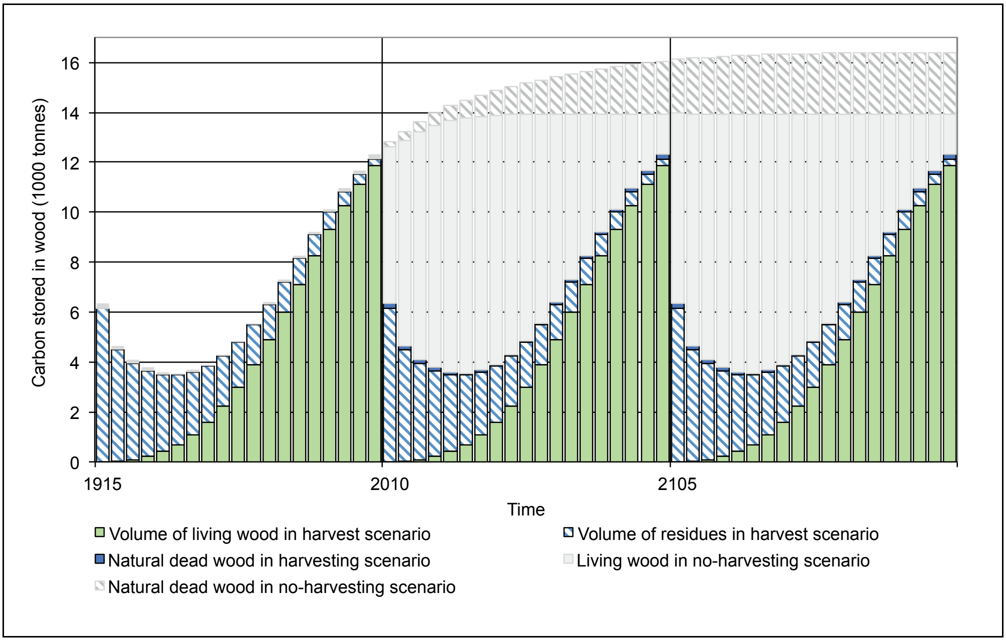

Figure 2. The dynamics of the carbon stock of a single stand, the basic building block of the H-model of the Norwegian forest. The colorized columns in the front show the development of the carbon stock in the harvest scenario. The considered stand was mature and harvested in 1915, 2010, 2105, 2200, and so forth. The grey columns in the background show the stand's carbon stock in the no-harvesting-scenario, i.e. no harvesting in 2010 or later.

Source: B. Holtsmark (2012)

As the productive part of the Norwegian forest covers an area of approximately 75 000 km^2, the H-model consists of 75 000 stands, each covering an area of one km^2. To make the model as transparent as possible, it was assumed that all stands have identical dynamic properties with regard to growth of living biomass and accumulation of dead organic matter. However, the time since the last clear-cutting varies and the distribution of the stands' ages is calibrated to fit data on the age distribution of the Norwegian forest provided by Larsson and Hylen (2007).

Essential for the dynamics of the H-model is that immediately after clear-cutting has taken place, the parcel's volume of living biomass drops to zero, and thereafter, the growth path begins again, see Figure 2. The volume of living biomass in a single parcel depends solely on the parcel's stand age. The parcel's productivity is fairly normal for a boreal forest and is close to the growth path of Norway spruce with productivity class 14 defined by Braastad (1975).

After clear-cutting, a share of the harvesting residues is left on the parcel. The stock of residues decomposes gradually, as illustrated in Figure 2. The accumulation of natural dead wood in each parcel of forest after clear-cutting and replanting is also shown in Figure 2.

In a boreal forest, in contrast to a tropical rain forest, a large share of the carbon is stored in the soil. According to Kjønaas et al. (2000), more than 80% of carbon in Norwegian forests is stored in the soil. An important question is therefore whether harvest is likely to trigger the release of carbon from soil. Such effects were not included in the H-model applied in the fourth essay. Effects on soil carbon, were, however, included in the models applied in the fifth and sixth essays, but did not turn out to be important for the results. The degree of uncertainty with respect to effects on soil carbon of harvesting is, however, significant, as discussed in the fourth essay.

1.12. Main results of the fourth essay and some additional simulation results

The findings of the fourth essay are based on simulations with the H-model described briefly above. Further details are given in the appendix to this essay.

Before giving a summary of the fourth essay, it should be noted that simulations with the H-model basically confirmed the findings of the NFLI-simulations reported in NEA (2010, 2011). However, the simulations with the H-model found a somewhat smaller drop in the forest's carbon stock over the 21st century if the harvesting level is increased to 15 Mm^3, see Figure 3. This difference is partly due to the inclusion of soil carbon dynamics in the NFLI-model, while effects on soil carbon is, as mentioned, not included in the H-model.

The H-model was simulated several hundred years into the future. In these simulations the forest's carbon stock stabilizes at a lower level in the high harvesting scenario compared to the scenario that sticks to the current harvesting level, see Figure 3. Hence, not even in the long term bioenergy is carbon neutral.[15]

Figure 2 provides the very simple explanation to this result. This diagram shows that the carbon stock of a stand at any point in time is greater in the non-harvesting case than in the harvesting case. In the high harvesting scenario an increased share of the stands follow the harvesting path instead of the no-harvesting path. It follows that the carbon stock of the forest also in the long term will be greatest in the low-harvesting scenario.

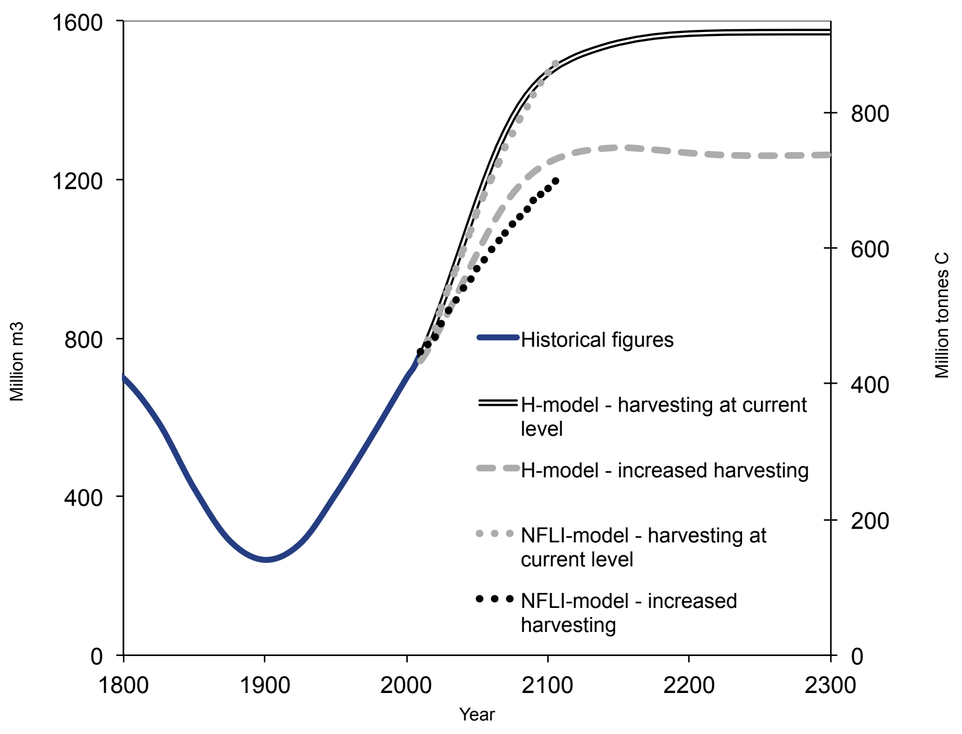

Figure 3. The stock of wood in the Norwegian forest, historically and in model simulations with both the H-model and the NFLI model.

Source: Norwegian Forest and Landscape Institute (historical figures), NEA (2011) and Statistics Norway.

It could here be argued that clear-cutting a stand is an opportunity to replace sparse or unproductive trees with more productive trees. The simulations shown in Figures 2 and 3 do not take that into account. The appendix to the fourth essay therefore includes a scenario that

[15] B. Holtsmark (2013a) discusses this in further detail and presents model simulations for the next 1000 years.

assumes that after clear-cutting and replanting, the density of the trees in all harvested stands is 25 per cent higher than the density of the standard parcel as they are described in Figure 2. This sensitivity analysis does not change the results fundamentally. The high harvest scenario still gives a smaller carbon stock than the low harvest scenario, also in the long term.

The next question analyzed in the fourth essay is whether there could be climate benefits of increased harvesting, despite the drop in the forest's carbon stock, if bioenergy replaces fossil fuels. Two cases are considered. In the first case, it was assumed that the wood is used as the raw material for manufacturing pellets. The pellets are assumed to replace coal in power plants. This is a relevant example because use of pellets to replace coal in power plants is taking place on an increasing scale in Europe (Lamers, Marchal, Heinimö, & Steierer, 2014). Furthermore, at the time of writing a large plant for production of pellets had recently been established on the west coast of Norway.[16]

The second example considers wood used to produce second-generation liquid biofuels. This example is relevant as NEA (2010) presented ambitious scenarios for the production of second-generation liquid biofuels based on wood. Moreover, recently the Norwegian company Statkraft and the Swedish company Söder are planning to start large scale production of second-generation liquid biofuels based on wood at Tofte in Norway.

Along the lines of Fargione et al. (2008), the fourth essay applies the concept *carbon debt,* which is defined as the net change in the accumulated emissions of carbon, taking into account both the drop in the forest's carbon stock due to the higher harvesting level and emission reductions when bioenergy replaces fossil fuels. Figure 4 illustrates the concept. The double-lined curve represents the drop in the forest's carbon stock that follows from increased harvesting. However, to find the net effect on atmospheric carbon, life cycle studies typically assume that the amount of bioenergy replaces a corresponding amount of fossil fuels, usually on a 1 kWh bioenergy against 1 kWh fossil energy basis. The dashed curve in Figure 4 represents that case, i.e. the net effect on accumulated emissions of CO_2 to the atmosphere when it is assumed that the supply of bioenergy replaces fossil fuels on a 1 kWh against 1 kWh basis. I return to the lack of realism in this approach due to leakage effects.

Nevertheless, with this approach there will be an initial period from t_0 to t_1 with enhanced concentration of CO_2 in the atmosphere, see Figure 4. The length of this period was

[16] BioWood at Averøya outside Kristiansund. The plan was to produce pellets for the European coal power plants based on Norwegian wood and was in an evaluation by Sjølie and Solberg (2009) considered to be environmentally beneficial. The project went bankrupt in 2014 and production was closed down.

by Fargione et al. (2008) labeled *the payback time of the carbon debt*. After time t_1 the CO_2 concentration of the atmosphere will be lower than in the case without bioenergy.

In the fourth essay, the payback time is found to be around 340 years if the harvest is used as raw material in the production of second-generation liquid biofuels. If the harvest instead is processed to pellets and replaces coal in power plants, the pay back time is found to be approximately 190 years.

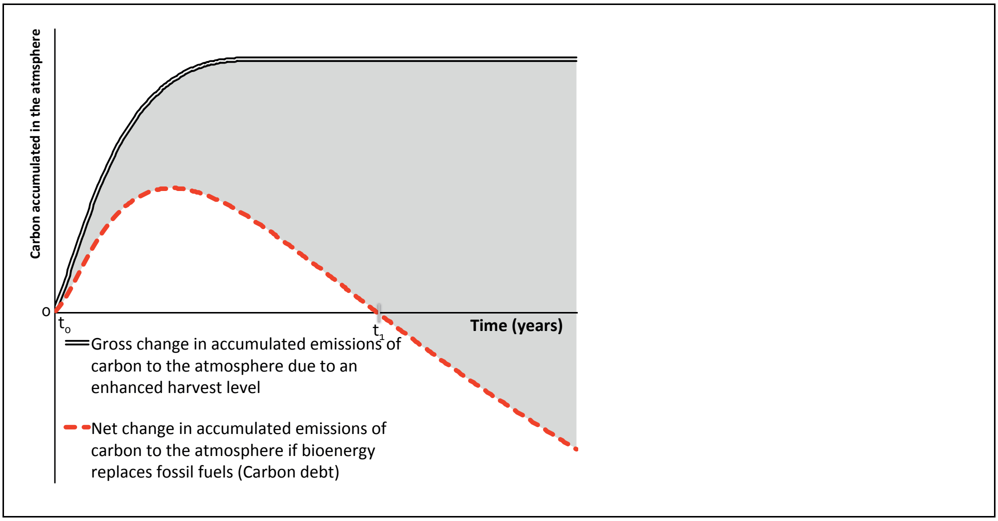

Figure 4. The change in accumulated emissions of carbon to the atmosphere due to a higher harvest level. The double-lined curve shows the case with no replacement of fossil energy, while the dashed line shows the case where bioenergy replaces fossil energy on 1 kWh bioenergy against 1 kWh fossil energy basis. Taking market effects into account means that a result within the grey area becomes more likely, see discussion in the sixth essay.

1.13. The global warming effect of wood fuels – summary of the fifth essay

Because bioenergy traditionally has been considered to be carbon neutral, CO_2 released from combustion of bioenergy (biogenic CO_2-emissions) has implicitly been given a global warming potential (GWP) factor of zero, for example in most LCA-studies.[17] With a GWP-factor of zero it has also been natural to exclude biogenic CO_2-emissions from carbon taxes and emissions trading regimes.

[17] GWP is a metric used to compare the climate impacts of GHGs. GWP quantifies the cumulative potential warming effect of a pulse of GHGs over a specified timeframe. GWP is a relative measure and the GWP of CO_2 is the benchmark and given the ratio 1.

However, as argued in the fourth essay, it is misleading to consider biogenic CO_2 as carbon neutral, at least CO_2 from combustion of wood from boreal forests. Other studies have come to the same conclusion, see for example Haberl et al. (2012), B. Holtsmark (2013a), Schulze et al. (2012), and Searchinger et al. (2009). The question is then how to quantify the warming potential of biogenic CO_2.

As a response to this new consensus and the questions that then arises, Cherubini, Peters, Berntsen, Strømman, and Hertwich (2011) introduced the concept GWP_{bio}, which was proposed as an indicator of the net potential warming of CO_2 released by combustion of biomass. GWP_{bio} should take into account not only the CO_2-pulse from combustion of the biomass, but how the harvest influences the net carbon flux between the considered forest stand and the atmosphere after the harvest, as the trees regrow. Later, also Cherubini, Strømman, and Hertwich (2011), Guest, Cherubini, and Strømman (2013), and Pingoud, Ekholm, and Savolainen (2012) presented estimates of GWP_{bio}. The mentioned studies found GWP_{bio} to be in the interval 0.34–0.62 when slow-growing forest stands were considered. The fact that these estimates are significantly below 1 could lead to the conclusion that bioenergy from slow-growing forests is 'an attractive climate change mitigation option' (Cherubini, Strømman, et al., 2011, p. p. 65).

The fifth essay, which is published in *GCB Bioenergy* (B. Holtsmark, 2015b), questions the results of those studies. The essay finds that the mentioned studies applied too restrictive models, for example abstracting from the dynamics of important carbon pools such as natural deadwood and soil carbon. Moreover, only Pingoud et al. (2012) included a representative baseline scenario. The other studies made the assumption that, if not harvested, there is no further growth and accumulation of carbon in a mature stand.

The fifth essay presents a different method for quantifying GWP_{bio}, by including a more comprehensive model of the dynamics of the carbon fluxes between the considered forest stand and the atmosphere. Moreover, the proposed method compares the harvest scenario with a no-harvest baseline scenario that takes into account that stands are usually harvested before growth has culminated (Faustmann 1849). Hence, there is growth and thus carbon capture also in the no-harvest scenario, although at a declining rate. Finally, the proposed method includes modeling the dynamics of all the forest's main carbon pools, including soil carbon, the pool of natural deadwood, and harvest residues, in addition to the stems. Including all carbon pools in the model is important because harvesting influences the dynamics of these pools, and thus the net carbon flux.

An important methodological difference between the fourth and the fifth essay should be mentioned. The fourth essay assumed as a simplification that CO_2-emissions accumulate in the atmosphere with no decay function, i.e. that CO_2 emitted to the atmosphere stays in the atmosphere forever. In agreement with other studies related to GWP_{bio}, the fifth essay makes this more sophisticated through application of the Bern 2.5CC carbon cycle model and its decay function based on Joos and Bruno (1996), Joos et al. (1996), and Joos et al. (2001). This model takes into account how a pulse of CO_2 leads to increased absorption of CO_2 by the terrestrial biosphere and the sea. The Bern 2.5CC model is also applied to all the fluxes of CO_2 between the considered stand and the atmosphere, for example the flux of CO_2 due to decomposition of natural deadwood and harvest residues left on the forest floor.

With the methodological improvements described above, the resulting GWP_{bio}-estimates are found to be 1.5 when no residues are harvested together with the stems. If 25 per cent of the residues are harvested, a share that corresponds to most of the tops and branches, GWP_{bio} is found to be 1.25. In other words, the estimates of GWP_{bio} was found to be two to three times as high as the estimates of GWP_{bio} found in other studies, and also significantly above GWP of fossil CO_2 when a 100 years time horizon was applied. Hence, the climate impact of bioenergy from slow growing forests seems to be higher than the climate impact of fossil fuels combustion, when a 100 years time horizon is applied.

A short comment is suitable on the result that GWP_{bio} is found to be lower when residues are harvested together with the stems. This might appear paradoxical as combustion of residues in addition to the stems increases the initial pulse of CO_2. However, keep in mind that GWP_{bio} is a relative measure (the warming potential per unit CO_2 of the initial pulse). If the residues had been left on the ground for decomposition, it would also gradually caused CO_2 emissions, increasing the warming potential per unit CO_2 in the initial pulse from combustion of the stems.

It also might appear paradoxical that the climate impact of CO_2 from bioenergy is found to be larger than the climate impact of CO_2 from fossil fuels. There are simple explanations to this result. First, the release of CO_2 from the decomposition of the residues left on the forest floor is significant and it comes in addition to the pulse-emission generated by the combustion of the harvested stems. Second, the dynamics of the pool of carbon stored in natural deadwood are important, and especially the lower accumulation of natural deadwood in the harvest scenario compared to the baseline no-harvest scenario. Third, in the no-harvest scenario, there is continued forest growth although at a declining rate, and there is continued accumulation of dead organic matter. Finally, the release of carbon from the soil after harvesting plays a role, although not a major one.

Nonetheless, when a very long time horizon, for example 500 years, is found more relevant, the fifth essay, as other studies, find that bioenergy becomes attractive from a climate perspective.

As mentioned above, previous studies estimated the GWP_{bio} to be significantly lower than found in the fifth essay. As the models applied in those studies are less comprehensive, an illustrative test would be to simplify the model applied in the fifth essay such that the applied model becomes similar to the models applied in earlier studies of GWP_{bio} and check whether the estimates of GWP_{bio} then are in agreement as well. Such tests were carried out and the fifth essay reports results of those model simulations. The results reported are in good agreement with results reported in the mentioned studies. This strengthens the conclusion that calculating the climate impacts of bioenergy from forests should be based on models that take into account the dynamics of all the forests' carbon pools and that previous estimates of the climate effects of bioenergy are too low.

1.14. A comparison of the global warming effects of wood fuels and fossil fuels – summary of the sixth essay

Like the fifth essay, the sixth essay applies the concept GWP_{bio} to quantify the global warming effect of bioenergy. The sixth essay is a slightly revised version of a paper published in *GCB Bioenergy* (B. Holtsmark, 2015a).[18] The sixth essay applies basically the same model of a forest stand as the fifth essay although a slightly different model for decomposition of forest residues was applied in the sixth essay. However, the sixth essay extends the analysis along three lines. First, it includes the cooling effects of increased albedo after clear-cutting. Second, it includes a comparison of the warming impact of bioenergy and fossil fuels, taking the CO_2-emissions per unit of energy into account. Third, the sixth essay follows up the discussion of the length of the payback time of the carbon debt introduced in the fourth essay.

With regard to the albedo effect, the essay adopts the methods and parameters applied by Cherubini, Bright, and Strømman (2012). They assumed that clear-cutting of a considered stand results in an immediate rise in albedo, not least because there will be a continuous snow surface during the winter season with high reflection of sunlight, if the stand has been clear-

[18] In addition to the main case with a climate sensitivity of 3 ºC, B. Holtsmark (2015a) considered a case with a climate sensitivity of 4.5 ºC. However, the way the parameters of the Bern 2.5CC were changed in this case could be criticized. The case is therefore left out in the sixth essay. Moreover, there are made some minor editing of the text.

cut recently. The albedo effect is then gradually reduced as regrowth takes place and the surface becomes less reflective during the winter season.[19]

When the albedo effect is not taken into account, the estimates of GWP_{bio} are almost identical to the results found in the fifth essay. The small differences are due to the slightly different model for decomposition of dead organic matter. When albedo effects are included in the calculations, the GWP_{bio} estimates become significantly lower. When residues (tops and branches) are collected together with the stems, the GWP_{bio} estimate drops to 0.75, when a time horizon of 100 years is applied. In the case without the collection of any residues, GWP_{bio} was found to be 1.1.

Next, the sixth essay carries out a comparison of the warming impact of wood fuels and fossil fuels. The result is that, when there are no albedo effects of harvesting and either a 100-year or a 20-year time horizon is applied, the warming impact of wood fuels is significantly higher than the warming impact of fossil fuels. The results are more ambiguous when an albedo effect of harvesting is included. The performance of wood fuels compared to fossil fuels then depends on whether residues are collected together with the stems. If residues are collected, the warming effect of wood fuels per unit of energy produced is approximately at the same level as oil when a 100-year time horizon is applied. If residues are not harvested, the warming effect of wood fuels is approximately at the level of coal when a 100-year time horizon is applied. If a time horizon of 500 years is applied, wood fuels have a smaller warming effect than all three types of fossil fuels, irrespective of the assumptions made.

Finally, the sixth essay leaves the single harvest approach and considers a permanent increase in the harvesting level, as also was done in the fourth essay. Moreover, comparisons are made with the warming effect of oil, coal, and natural gas. A methodological improvement compared to the fourth essay is to apply the Bern 2.5CC carbon cycle model. Both the limiting cases with no substitution and full substitution (1 kWh bioenergy replaces 1 kWh fossil fuels) were considered in order to capture the full range of possible outcomes.

As the fourth essay, the sixth essay provides estimates of the payback time of the carbon debt. This payback time was found to be 140 years if there is full substitution of coal (1 kWh bioenergy replaces 1 kWh coal). If bioenergy replaces oil or gas, the payback time is significantly longer.

If less optimistic assumptions are made about how much fossil fuels are replaced by the increased supply of bioenergy, the payback time becomes longer. The inclusion of the

[19] Lutz and Howarth (2014) study the importance of albedo for forest management in case of temperate forests south of the boreal forest belt.

albedo effects of harvesting results in a picture that is significantly more in favor of bioenergy, with shorter payback times. If there is full substitution of coal, the albedo case means that there is a net cooling effect of harvesting from day one. However, if less substitution is assumed, the picture will be less in favor of bioenergy.

The payback time found in the sixth essays is somewhat shorter than found in the fourth essay. One reason for this is that the sixth essay applies the Bern 2.5CC carbon cycle model, while the fourth essay applied a simple accumulation model with no decay function.

1.15. Forest management when there is a social cost of CO_2-emissions – summary of the seventh essay

As the preceding three essays, the seventh and last essay studies forest management in relation to the climate issue. However, the approach taken is different. The three preceding essays studied how harvesting a slow growing boreal forest influences global warming when the harvest is used as bioenergy. The fourth and the sixth essays in addition compared the warming effect of bioenergy with the warming effect of fossil fuels. The seventh essay has a more classical economic approach and has as starting point that there is a social cost of carbon emissions and analyses how this should influence forest management. The seventh essay is a joint work with Michael Hoel and Katinka Holtsmark. It is published in *Journal of Forest Economics* (Hoel, Holtsmark, & Holtsmark, 2014).

The approach taken in this essay is relevant in a situation where there is a tax or a similar instrument related to combustion of fossil fuels that corresponds to the social cost of carbon. The basic research question studied is how forests should be managed in this situation, given that a certain share of the harvest is used for bioenergy, while the remaining share is used as building material or other durable goods. To simplify the analysis, it is assumed that the social cost of carbon is assumed to be constant over time, which means that the present value is decreasing over time.

Faustmann (1849) was the first to develop a correct formula (the Faustmann Rule) for determination of the length of the rotation period when a forest owner's goal is to maximize the discounted yield, taking account of the discounted yield from all future rotations. The main contribution of the essay is to develop an adjusted Faustmann Rule when there is a social cost of carbon emissions, taking into account the dynamics and interactions of the forest's multiple carbon pools. Numerical examples illustrate the theoretical results.

Among other theoretical studies of the issue, van Kooten, Binkley, and Delcourt (1995) and McDermott et al. (2015) represent to my knowledge the most thorough studies.

They applied a multi-rotation infinite time horizon model and provided an adjusted Faustmann Rule when there is a social cost of carbon emissions. However, the theoretical framework of these two studies did not incorporate the dynamics of important carbon pools such as roots, stumps, tops and branches, harvest residues and naturally dead organic matter, which the seventh essay shows are important elements in construction of an adjusted Faustmann Rule.

Asante and Armstrong (2012) is another theoretical contribution, see also Asante, Armstrong, and Adamowicz (2011). In contrast to van Kooten et al. (1995) and McDermott et al. (2015), they included the forests' multiple carbon pools in their model. At the same time they considered a single rotation model only and their time horizon was limited to the length of the single rotation. B. Holtsmark, Hoel, and Holtsmark (2013) discussed the results of Asante and Armstrong (2012) and found that their main results followed from their limited time horizon and could be misleading. This made evident the need for a theoretical, multi-period infinite horizon analysis of the issue, which includes the dynamics of the forests' main carbon pools. Therefore, the seventh essay presents a comprehensive theoretical analysis that combines the multi-rotation infinite time horizon model of van Kooten et al. (1995) with the multiple carbon pools approach of Asante and Armstrong (2012) and Holtsmark et al. (2013).

The findings of the seventh essay could be summarized as follows. First, consider a forest with positive net commercial profit from harvesting. In that case, if the rotation period that maximizes social welfare is finite, the adjusted rule implies that the optimal rotation length is strictly increasing in the social cost of carbon. Depending on the parameters, it may be the case that a finite rotation length is optimal no matter how large is the social cost of carbon emissions. There may also exist a threshold value for the social cost of carbon, above which the stand should not be harvested. It could here be mentioned that the simulations with the numerical forest model show that for reasonable discount rates and parameter values, a threshold value actually exists above which the forest should not be harvested.

Second, consider the case when there is *negative commercial profit* from harvesting. If there is a positive social cost of carbon emissions that is lower than a certain threshold level, then it is optimal to never harvest the stand. If the social cost of carbon is *above* the mentioned threshold level, depending on the parameters, it could in theory give a social surplus to harvest. If so, then the adjusted Faustmann Rule implies that the optimal rotation length is strictly *decreasing* in the social cost of carbon. It is difficult to give good intuition to this result. However, a social surplus from harvesting when the commercial profit is negative appears to be an unlikely case. Numerical simulations showed that for reasonable discount rates and parameter values, the stand should never be harvested if there is a negative commercial profit.

The main driver of the results of the seventh essay is the assumption that the present value of the social cost of carbon is decreasing over time – emissions in the future are preferred over emissions today. This seems a reasonable assumption, and is elsewhere in the literature often either assumed or derived from other assumptions of the analysis. A single harvest leads to an increase in the stock of carbon in the atmosphere in the short run, and the damage resulting from this increase would have been postponed with a longer rotation period.

Compared to other theoretical studies, the contribution of the seventh essay is to investigate the issue in a considerably less restrictive theoretical framework. We take into account that less than half of the carbon in the forests' biomass is contained in the tree trunks. Tops, branches, roots and stumps constitute approximately half of the carbon stored in living biomass, and to the extent that these components are not harvested together with the trunks, they will gradually decompose and release carbon to the atmosphere. The dynamics of these carbon pools as well as the stock of natural deadwood is included in both the theoretical and numerical analyses. In addition, we allow an exogenous fraction of tops, branches, roots and stumps to be harvested and used for energy purposes. And finally, the dynamics of a stock of carbon stored in building materials and furniture is also taken into account. With our less restrictive approach, including both multiple rotation periods and multiple carbon pools in the analysis, the threshold value of the social cost of carbon above the threshold value at which harvest should not take place, is significantly lower than found in studies with a more restrictive approach. The multiple-carbon-pool-approach also means that the effect of a social cost of carbon on the length of the rotation period is significantly stronger than found in previous theoretical studies with more restrictive models. To fully understand the mechanisms behind the effect of a social cost of carbon on the optimal length of the rotation period, our less restrictive model turns out to be important. We found that increasing the share of residues harvested and/or the share of stems used for durable storage in buildings and furniture reduces the effect of a social cost of carbon on the optimal rotation period. Conclusions regarding the effect on the optimal rotation periods of changes in harvesting procedures or use of harvested material might potentially have important policy implications.

1.16. Closing comments

Finally, a few words about what can be concluded from this thesis, and some unresolved issues that have become more visible.

Regarding the first three essays, they do not give any final answers on how to make international cooperation on climate change more effectively. Hopefully, however, they give some contributions to the accumulation of knowledge related to important questions. The games presented in the second and third essays lead to conclusions that question the benefits of emissions trading. However, the exercises of these two essays are based on stylized models and are not sufficiently complete to warrant any strong policy implications. It is also important to note that other contributions provide conclusions that point in a different and more optimistic direction. Nevertheless, the findings of the second and third essays demonstrate that there are some mechanisms that are important to understand and be aware of in the design of agreements with emissions trading. The fact that the literature on the field gives divergent conclusions also emphasizes the need for more research in the field. As emissions trading is central to international cooperation on climate change, this could be important.

Regarding the last four essays about bioenergy from slow-growing boreal forest, they provide the basis for somewhat stronger conclusions. What seems pretty clear is that the classical assumption that bioenergy is carbon-neutral does not hold. The last four essays clearly show that increased logging for energy purposes in boreal forests could increase the concentration of CO_2 in the atmosphere for a long time, probably throughout the 21st century and even further into the future. At the same time, there is little doubt that on the very long term, such a policy could lead to lower CO_2 content in the atmosphere, if bioenergy replaces fossil fuels efficiently. Without efficient replacement of fossil fuels, increased use of bioenergy could amplify the CO_2 problem.

However, also when it comes to the last four essays of the thesis, the results should not be overinterpreted. Although I find that earlier studies might have overestimated climate benefits of bioenergy from forests, this does not mean that bioenergy in general is harmful. Much of today's bioenergy is made of waste from different wood-based industries. If such waste is used for energy purposes and replaces fossil fuels, it gives climate benefits. The primary purpose of the thesis is not to study that type of bioenergy, but rather to study whether increased logging for energy purposes gives climate gains. This is a relevant issue since harvesting is increasing in several countries just to increase the supply of bioenergy (Lamers et al., 2014). In this perspective, the mentioned findings are relevant.

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